Fiber Properties Preview

- Optical attenuation
  - Power loss in fiber
    - » Causes...
      - Absorption and scattering in glass
      - Glass impurities, fiber imperfections, bends
    - » Minimum loss at 1550 nm

- Fiber dispersion
  - Pulse spreading limits maximum data rate
  - Causes
    - » Fiber modes
    - » *n* is function of wavelength
    - » Waveguide effects
  - Zero dispersion near 1300 nm

- Nonlinear effects
  - Accumulate over long distances
  - Limit maximum power that can be put into a fiber

Props-1

Fiber Loss: Attenuation Factor

- **Optical power decreases exponentially as light travels through fiber**

$$P(z) = P(0)e^{-\alpha_p z}$$

Attenuation factor α **(dB/km)**

- **Expressed as dB/km loss**

$$\alpha = \frac{-10\log\left(P(z)/P(0)\right)}{z}$$

- **Typical values: few tenths $\rightarrow$ few dB/km**
- **Wavelength-dependent**

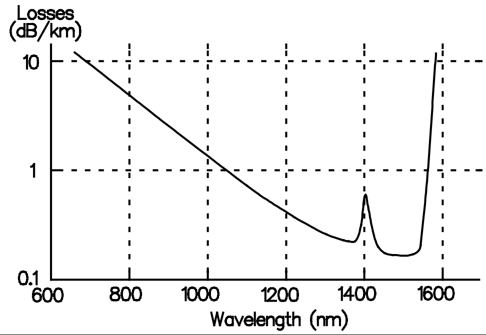


Fig. 3.1 p. 34

Fiber Loss: Numerical Example p. 35

- Optical fiber losses: 0.6 dB/km at 1300 nm. If 100 μW of power at transmitter, how much power at 22 km?
- Use dBm
- See classroom discussion

Props-3

Fiber Loss: Attenuation (cont.)

- **Factors:**
  - **Material absorptions**
  - **Impurity absorptions**
  - **Scattering effects**
  - **Interface inhomogeneities**
  - **Radiation at bends**

Props-4

- Material absorptions: Silica (SiO_2) absorption
- Impurity absorptions
  - ☞ Impurity metals
  - ☞ H_2O vapor
- Scattering effects
  - ☞ Molecular scattering (~●-1/4); long-wavelength limit
  - ☞ Mie scattering
  - ☞ Nonlinear scattering
- Interface inhomogeneities
  - ☞ Particles
  - ☞ Geometry defects
- Bend losses
  - ☞ MM fiber: geometry changes light couples out of core
  - ☞ SM fiber: light tries to accelerate beyond c/n; radiates power
  - ☞ Negligible below critical turn radius of ~ 1 cm

Fiber Loss: 1. Material Absorption

1. Molecules of basic fiber material (silica = SiO_2)
   - Fundamental loss limit at high λs
     - » Change materials to lower loss ("Ultralow-loss" fiber)
2. Material impurities
   - Metallic ions (remove by purifi-cation)
     - » Iron, cobalt, copper, chromium
       - ppb (parts per billion) concentrations
   - OH^- water ion (remove by chlorine drying)
3. Hydrogen effects
   - Increased losses at 1.2 and 1.6 μm
   - Produced by
     - » Corrosion or
     - » Bacteria
   - Increases loss by interaction with glass
   - Solution:
     - » Eliminate H_2 sources or
     - » Add impermeable coating to fiber

Props-5

Fiber Loss: 2. Scattering Loss

- Wave interacts with "particle" or molecules
- Transfers power to other directions

  a. Linear scattering:

  » Scattered power proportional to incident power

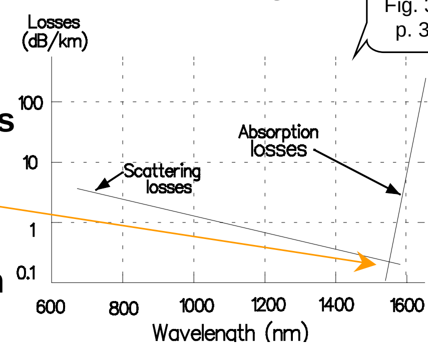
  » No change in frequency of scattered light

  » ***Rayleigh scattering***:

  - Particles << λ
    - Molecules, changes in *n* (change in composition), changes in density
  - Scattering strength ~$1/\lambda^4$
  - Fundamental loss at low wavelengths
    - Minimum loss at 1550 nm in silica (SiO_2)
    - Theoretical minimum ~0.15 dB/km

"Magic wavelength #1"

Fig. 3.2 p. 38



Props-6

Fiber Loss: 2. Scattering Loss (cont.)

a. Linear scattering **(cont)**

- ***Mie scattering***
  - **Particles ~λ**
    - **Inhomogeneities**
      - **Core-cladding refractive index variations**
      - **Core-cladding interface impurities**
      - **Diameter fluctuations**
    - **Strains in fiber**
    - **Bubbles in fiber**
  - **Solution:**
    - **Remove imperfections**

Props-7

Fiber Loss: 2. Scattering Loss (cont)

b. Nonlinear Scattering

- **Cause: high *E* field (V/m)** **(i.e., combination of power, area, and distance)**
- **Power scattered forward, backward, or side directions,** **depending on interaction**

***A. Brillouin scattering*:**

» **Photon undergoes nonlinear interaction to produce...**
  - **Vibrational energy ("phonons") and**
  - **Scattered light ("photons")**

» **Upward and downward frequency shifts**
  - **Strength of scattering varies with scattering angle**
    - **Maximum in backward direction; minimum of zero in forward direction**

» **Solution: keep power level below threshold**
  - **Nonlinear scattering imposes "ceiling" on source power**
  - **Threshold power level**

$$P_B = \left(17.6\times10^{-3}\right)a^2\,\lambda^2\,\alpha\,\Delta\upsilon' \quad \text{(typically } \leq 1 \text{ W in SM fiber)}$$

Props-8

- Ex., 8/125 SM fiber with 0.8 dB/km loss at 1300 nm; source $\Delta\lambda$ of 0.013 nm,
  $\Rightarrow P_B$ = 0.879 W.

Fiber Loss: 2. Scattering Loss (cont.)

b. Nonlinear Scattering (cont)

***B. Raman scattering*:**

» **Nonlinear interaction produces….**

- **High-frequency phonon (instead low-frequency phonon of Brillouin scattering)**
- **Scattered photons**

» **Scattering predominantly in *forward* direction (power not lost)**

» **Power level threshold:**

$$P_{\text{Raman}} = \left(23.6\times10^{-2}\right)a^{2}\,\lambda'\alpha \;\; \text{(typically few W)}$$

» **Solution: keep power level below threshold**

- **Single channel fiber**
  - **Brillouin threshold lower than Raman and determines power "ceiling"**

Props-9

- Ex., 8/125 SM fiber with 0.8 dB/km loss at 1300 nm; source $\Delta\lambda$ of 0.013 nm,

  $\Rightarrow$ P_R = 3.93 W

Fiber Loss: 3. Interface Inhomogeneities

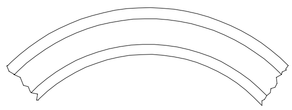
- **Some typical inhomogeneities**
  - **Impurities trapped at core-cladding interface**
  - **Impurities in fiber buffering**
  - **Geometrical changes in core shape and/or size**
- **SM fibers more susceptible**
- **Solution: Remove source of problem**
  - **Manufacturing quality control**

Props-10

Fiber Loss: 4. Bend Losses

A. Macrobends

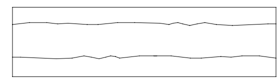
- Large bends of cable and fiber



- At bend, core/cladding angle of incidence changes and power lost
- Lost power depends on bend radius
  - » Negligible losses until bend radius reaches critical size (typically < 1 cm)
  - » Solution:
    - Limit bend radius
    - Add cable stiffener

B. Microbends:

- Small-scale bends in core-cladding interface



- Develop during fiber deployment or local mechanical stresses
- Develop due to cabling, spooling, or wrapping fiber on bobbin
  - » *Cabling loss* and *spooling loss*
  - » Typical added loss:
    - ✠ 1 to 2 dB/km
  - » Solution (partial) : careful winding

Props-11

- Expression for critical bend radius:

$$r_{\text{critical}} \approx 3n_2 \lambda / 4\pi \, \text{NA}^3$$

Fiber Loss: 4. Single-Mode Fiber Bend Loss

- **Bend loss particularly important in SM fiber**
- **Dramatic loss increase above critical wavelength if fiber bent or perturbed**
  - **Appreciably high @ 1550 nm in 1300-nm designed fibers**
  - **Susceptibility depends on MFD and λ_{cutoff}**
  - **Worst-case is fiber with...**
    - » **Large MFD and low λ_{cutoff}**
    - » **Avoid this combination!**
- **Minimize bend losses by...**
  - **Choosing small ratio of core to fiber diameter**
  - **Having large Δ and/or...**
  - **Jacketing with compressible material**

Props-12

Loss Summary

- **Loss in fiber due to…**
  - **Absorption**
  - **Scattering (linear and nonlinear)**
  - **Fiber inhomogeneities**
  - **Bends**
    - » **Macrobends**
    - » **Microbends**

- ***Intrinsic losses* due to**
  - **Absorption**
  - **Scattering**
- **Minimum loss at 1.55 μm**
- **Theoretical minimum loss (~0.15 dB/km) almost achieved in practice**

Props-13

Loss Measurements

- Insertion loss measurement
  - –Uses optical source and optical power meter
  - –Measure loss of piece of fiber
  - –Add fiber to be tested
  - –Extra loss is loss of fiber (plus connector/splice losses)
- Cutback method
  - –Uses optical source and opt1cal power meter
  - –Measure loss of fiber under test
  - –Delete some length of the fiber
  - –Reduction of loss is loss of fiber
- Optical Time Domain Reflectometer (OTDR)
  - –See following discussion

Props-14

OTDR

- OTDR - Optical Time-Domain Reflectometer
- Ubiquitous fiber optic instrument
- Requires access to only one end of fiber
- Can measure
  - Fiber length
  - Distance to fiber breaks, connections, splices
  - Fiber loss (dB/km)
  - Connector and splice loss

Props-15

OTDR Operation

- **Consists of pulsed laser, detector, electronic processing**
- **Weak backscatter from glass molecules**
- **Pulsed source, time-gated receive**
- **Received power level stored in memory**

Fig. 3.4
p. 44

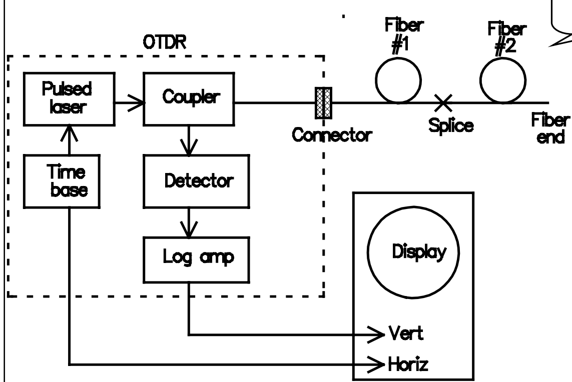
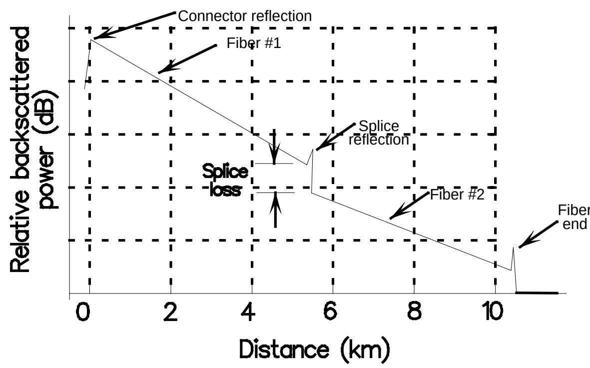


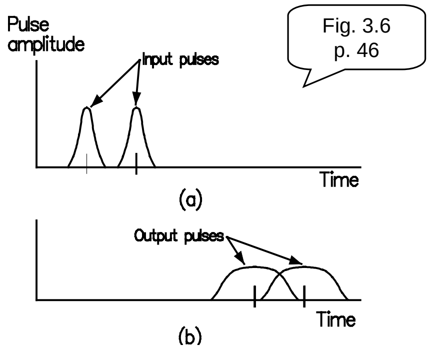
Fig. 3.5
p. 45



- See problems 4, 5, 6, and 8 for details.

Dispersion in Optical Fibers

- **Pulse spreads as it propagates; overlapping causes intersymbiol interference**



- **Amount of spreading**
  - **Limits how close (in time) two adjacent output pulses are**
  - **Limits maximum data rate**
- **Primary sources of spreading in fibers:**
  - ***Group velocity dispersion***
    - » **Material dispersion**
    - » **Waveguide dispersion**
  - **Modal dispersion**

Props-17

Group Velocity Dispersion

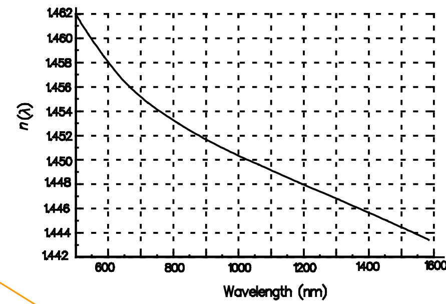
- GVD - Group velocity dispersion
- Consists of
  - Material dispersion
  - Waveguide dispersion
- We consider each separately and add effects together

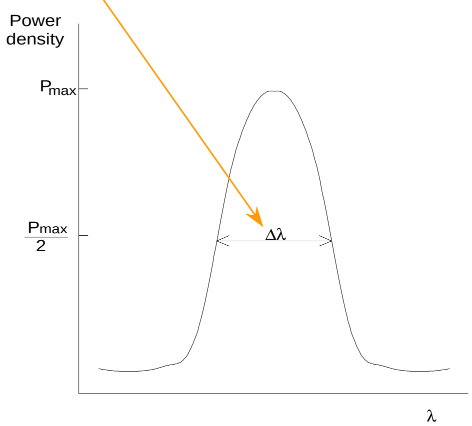
Props-18

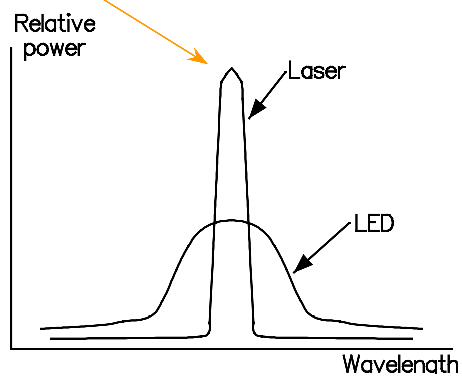
Fiber Dispersion: A. Material Dispersion

Fig. 3.7
p. 47

- **Velocity of light in SiO_2 is weak function of wavelength, *n(λ)***
- **All light sources have *spectral width* Δλ**
  - **Lasers narrower spectrum than LEDs**
- **Longer λs arrive at RCVR before shorter λs**







Props-19

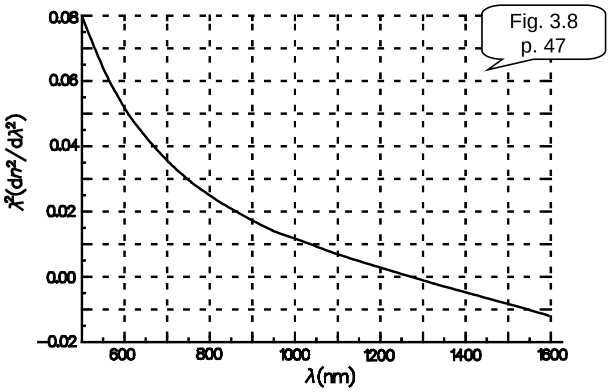
- Ex.: material dispersion in a 62.5/125 fiber with $n_1 = 1.48$ and $\Delta = 1.5\%$ is 86.3 $ps \cdot km^{-1} \cdot nm^{-1}$ at 850 nm and is +35.6 $ps \cdot km^{-1} \cdot nm^{-1}$ at 1500 nm

Material Dispersion (cont.)

- **Pulse spread due to material dispersion**

$$\Delta\tau_{\text{mat}} = -\frac{L}{c}\frac{\Delta\lambda}{\lambda}\underbrace{\left(\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right)}_{\text{Figure 3.8, p. 47}}$$

- **Frequently normalized: $D_{mat}=\Delta\tau_{mat}/(L\Delta\lambda)$ [ps·km^{-1}·nm^{-1}]**



Props-20

Fiber Dispersion: B. Waveguide Dispersion

- **In low material-dispersion region of 1000 to 1600 nm in SM fibers...**
  - ***Waveguide dispersion* becomes important**
  - **Negligible in MM fibers and in SM fibers operated below 1,000 nm and above 1600 nm**
- **Cause: velocity of mode is function of *a/*λ**
- **Waveguide dispersion**

$$\Delta\tau_{wg} \approx -\left(\frac{n_2 L\Delta}{c}\right)\left(\frac{\Delta\lambda}{\lambda}\right)\underbrace{\left(V\frac{d^2(Vb)}{dV^2}\right)}_{\text{Fig. 3.10, p. 51}}$$

$D_{WG} = \Delta\tau_{WG}/L\,\Delta\lambda$ [ps·km^{-1}·nm^{-1}]

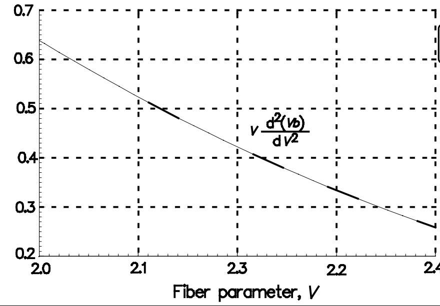


Fig. 3.10 p. 51

Props-21

- Ex.: At 1300 nm, 9/125 single-mode fiber with n_1 = 1.48 and Δ = 0.22%

  $\Rightarrow$ D_{WG} = –4.00 ps·km^{-1}·nm^{-1}

Fiber Dispersion: Zero-Dispersion SM Fiber

- **SM fiber:**
  - ***Total dispersion = group velocity dispersion* = material + waveguide dispersions**
- **Small positive material dispersion can cancel small negative waveguide dispersion**
  - **Result: zero dispersion (at single λ)**
  - ***Zero-dispersion point in SM fiber occurs near 1300 nm***

"Magic" wavelength #2

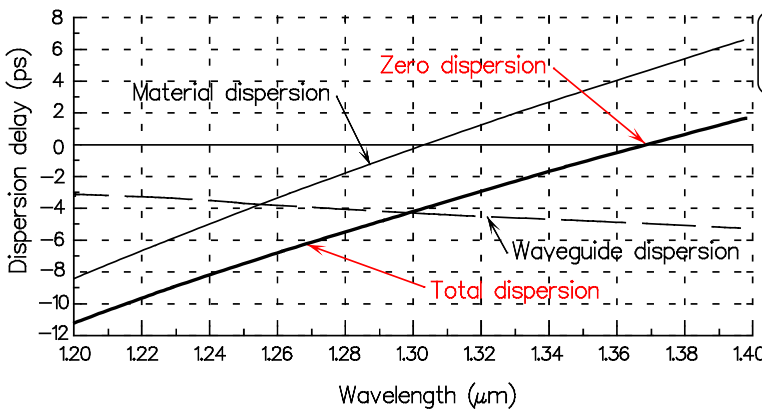


Fig. 3.11
p. 52
revised

Props-22

Fiber Dispersion: Dispersion-Adjusted SM Fibers

- **Waveguide dispersion sensitive to...**
  - **Doping levels, *a*, λ, *n(r)***
- **Achieve zero dispersion at other wavelengths**
  - **anywhere from 1300 to 1700 nm**
  - **Ex., Combine at 1550 nm**
    - » **Minimum losses**
    - » **Zero dispersion**
    - » **Called *dispersion shifted fiber***

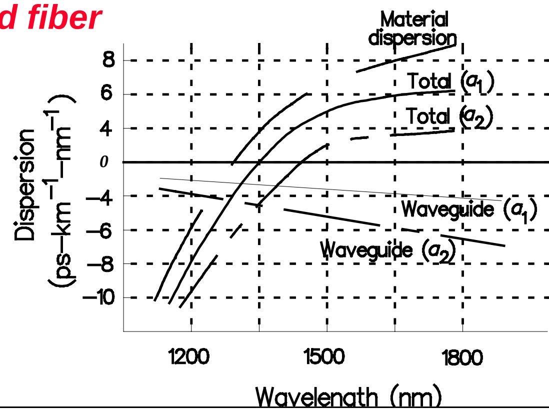


Fig. 3.12 p. 53

Props-23

Fiber Dispersion: Dispersion-Flattened Fibers

- **Alternative approach:**
  - **Reduce dispersion to nonzero minimum between 1300 and 1500 nm**
  - **Allows use of both 1300 & 1500 nm sources**
    - » **Reasonable loss and dispersion**
- **Called *dispersion flattened fiber***
- **Multiple-cladding fibers successfully used**

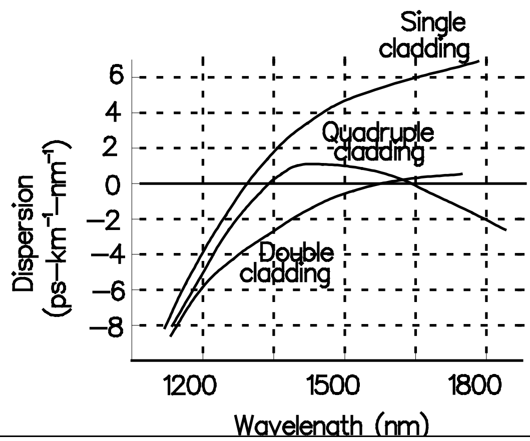


Fig. 3.15 p. 57

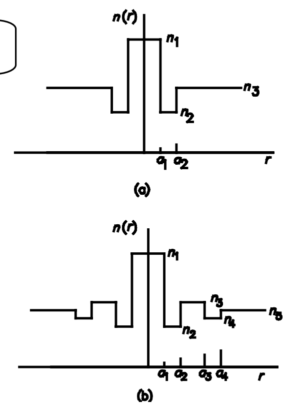
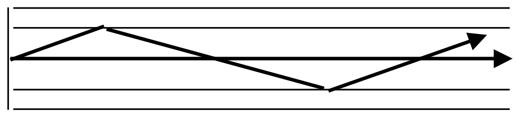


Fig. 3.14 p. 56

Fiber Dispersion: C. Modal Dispersion

- ***Only*** **in multimode fibers**
- **Cause:**
  - **Each mode has slightly different path to receiver**



- **Time delay between fastest and slowest is modal pulse delay distortion and in SI fiber is...**

$$\Delta\tau_{\text{SI modal}} = \frac{L(n_1 - n_2)}{c}\left(1 - \frac{\pi}{V}\right) \approx \frac{L(n_1 - n_2)}{c} = \frac{L\Delta n_1}{c}$$

  - $D_{modal} = \Delta\tau_{modal}/L$ **[ps·km^{-1}]**

Props-25

- Ex.: 50/125 step-index fiber with $n_1 = 1.47$ and $\Delta = 1.5\% \Rightarrow \Delta\tau_{modal}/L \approx 73.5$ ns·km^{-1}

Modal dispersion II: Graded-Index Fibers

- **GI fiber**
  - **Variable light velocity**
  - **Sinusoidal paths**
- **High-order modes have longer path lengths *but* also have higher average velocity**
  - **Longer path length approximately canceled by higher velocity**
- **Delay time of *m*-th mode….**

Eq. 3.64
p. 58

$$\tau_{\text{GI modal}} = \frac{LN_{g1}}{c}\left(1+\frac{g-2-\varepsilon}{g+2}\Delta\left(\frac{m}{N}\right)^{\frac{g}{g+2}} + \frac{\Delta^2}{2}\frac{3g-2-2\varepsilon}{g+2}\left(\frac{m}{N}\right)^{\frac{2g}{g+2}} + \text{ other terms of } \Delta^3,\ \Delta^4,\ \text{etc}\right)$$

$$\varepsilon = -\frac{2n_1}{N_{g1}}\frac{\lambda}{\Delta}\frac{d\Delta}{d\lambda},\quad N_{g1} = n_1\lambda\frac{n_1}{\lambda}\frac{dn_1}{d\lambda},\ \text{and}\quad N = a^2\Delta k^2 n_1^2\frac{g}{g+2}.$$

Props-26

Modal Dispersion II: GI Fibers (cont.)

- **Linear term in Δ can be eliminated if...**

$$g = g_{\text{opt}} = 2 - \frac{2n_1}{N_{g1}}\frac{d\Delta}{d\lambda}$$

  - **Usable approximation is**

$$g_{\text{opt}} \approx 2 - \left(12\Delta/5\right)$$

- **Net delay is**

$$\Delta\tau_{\text{GI modal}} \approx \begin{cases} n_1\Delta\dfrac{g-g_{\text{opt}}}{(\mathrm{g}+2)\mathrm{c}} & \mathrm{g} \neq \mathrm{g}_{\text{opt}} \\ \dfrac{\mathrm{n}_1\Delta^2 L}{2c} & \mathrm{g} = \mathrm{g}_{\text{opt}} \end{cases}$$

  - **$\Delta\tau_{\text{modal}}$ can be positive or negative**
- **GI modal dispersion factor of ~Δ smaller than SI**
  - **Max bit-rate of GI is ≥100x max bit-rate of SI**

Props-27

Fiber Dispersion: Dispersion Units

- **Modal dispersion:**
  - **Dominates in MM fibers**
    - **Less in GI fibers than SI fibers**
  - **Depends on *L***
  - **Independent of $\Delta\lambda$**
    - **Normalized units of [ns·km^{-1}]**
    - **Can be given as analog bandwidth-distance product: [GHz·km]**
- **Material dispersion and waveguide dispersion:**
  - **Dependent on $\Delta\lambda$ and *L***
  - **Normalized units of [ns·km^{-1}·nm^{-1}]**

Props-28

Bit-Rate and Dispersion

- **Maximum bit rate**

$$B_{R\,\max} \approx \frac{1}{4\Delta\tau_{\text{total}}}$$

where

$$\Delta\tau_{\text{total}} = \sqrt{\Delta\tau^2_{\text{modal}} + \Delta\tau^2_{\text{GVD}}} \qquad \text{and} \qquad \Delta\tau_{\text{GVD}} = \Delta\tau_{\text{material}} + \Delta\tau_{\text{waveguide}}$$

- **Note that $B_{R\,max} \sim 1/L$**
- **(bit-rate)-distance product is constant for a given fiber**

Props-29

Fiber Dispersion: Summary

- **Total dispersion:**
  - **Multimode fibers: modal dispersion and material dispersion**
  - **Single-mode fiber: material dispersion and waveguide dispersion (1000 nm to 1600 nm only)**
  - **Near 1300 nm, dispersions can cancel**
- **Dispersion ~*L***
  - **Max bit rate ~ 1/$\Delta\tau$ ~ *1/L***
    - » **Max bit rate $\times$ *L* is constant**
- **Fibers specified by bit rate-distance product**

Fiber Type	(Bit-rate)•distance product
Single-mode	Many Gb/s•km
Step-index multimode	Few 10s Mb/s •km
Graded-index multimode	Several 100s Mb/s •km

Props-30

- Bit rate-distance trade-off
  ☞ Longer distances require reduction of bit rate

Dispersion: RMS Pulse-Spreading Approach

- **Alternative approach to delay times**
- **Define RMS pulse width**

$$\sigma_s = \sqrt{\int_{-\infty}^{\infty} t^2 p(t)dt - \left(\int_{-\infty}^{\infty} tp(t)dt\right)^2} = \sqrt{\int_{-\infty}^{\infty} t^2 p(t)dt} \quad \text{(for symmetric wave)}$$

- **Relate input and output pulse widths**

$$\sigma_{\text{out}}^2 = \sigma_{\text{in}}^2 + \sigma_{\text{fiber}}^2$$

where

$$\sigma_{\text{fiber}}^2 = \sigma_{\text{modal}}^2 + \sigma_{\text{GVD}}^2 = \sigma_{\text{modal}}^2 + \left(\sigma_{\text{material}} + \sigma_{\text{waveguide}}\right)^2$$

where

$$\sigma_{\text{modal}}(\text{SI}) \approx \frac{Ln_1\Delta}{c} = \frac{L\,(\text{NA})^2}{4\sqrt{3}\,n_1 c} \qquad \sigma_{\text{mod}\,al}(\text{GI}) \approx \begin{cases} \dfrac{0.246\,LN_{g1}\Delta\left|g - g_{opt}\right|}{c(g+2)} & 1 > \left|g - g_{opt}\right| >> \Delta \\ \dfrac{0.150\,LN_{g1}\Delta^2}{c} \approx \dfrac{n_1\Delta L}{2c\sqrt{3}} & g = g_{opt} \end{cases}$$

$$\sigma_{\text{material}} \approx \frac{L}{c}\left(\frac{\sigma_\lambda}{\lambda}\right)\left(\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right) \quad \text{and} \quad \sigma_{\text{waveguide}} = -\frac{n_2 L\Delta}{c}\left(\frac{\sigma_\lambda}{\lambda}\right)\left(V\frac{d^2(Vb)}{dV^2}\right)$$

Props-31

Fiber Nonlinearities Revisited

- **Nonlinear effects used to be negligible for modest powers and distances**
- **Now cause problems because of power levels (and multiple signals) and long distances**

$$E(z+dz) = E(z)e^{\left(-\frac{\alpha_p}{2}+jk+\underbrace{\frac{\gamma P(z)}{2A_{eff}}}_{\text{nonlinear term}}\right)dz}$$

- **The nonlinear coefficient, γ, is small. Large power, small core area, and/or long distance make effects noticeable**
- **Nonlinear fiber parameters**

Effective area

$$A_{eff} = \frac{\left(\iint I(r,\theta) r\,dr\,d\theta\right)^2}{\iint I^2(r,\theta) r\,dr\,d\theta} \approx A_{\text{wave}} = \pi(\text{MFD})^2$$

Effective length

$$L_{eff} = \frac{1-e^{-\alpha_p L}}{\alpha_p} \approx \frac{1}{\alpha_p} \text{ (for L >> } 1/\alpha_{\text{p}})$$

Props-32

Fiber Nonlinearities (cont.)

- Nonlinear coefficient, γ, is small and can be…
  - real (a gain or loss) or
  - imaginary (phase effect)
- Stimulated scattering
  - » Raman scattering
  - » Brillouin scattering
- Nonlinear index effects
  - » Single-signal
    - Self-phase modulation
  - » Multi-signal
    - Cross-phase modulation
    - Four-wave mixing

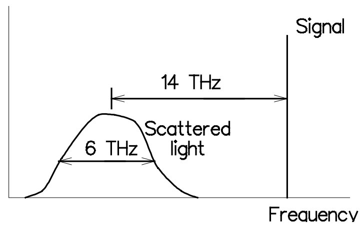
Props-33

Nonlinear Scattering

- **Interaction of photon and phonon to produce *frequency-shifted* photon**

$$\nu_{out} = \nu_{in} - \nu_{phonon}$$

- **Stimulated Raman scattering**
  - **Input light causes generation of scattered light**
  - **Coherent scattered light coherent**
  - **Scattered light is broad ($\Delta\nu$ ~ 6 THz) with center frequency 14 THz below input frequency**



  - **Scattered light takes energy from signal and grows exponentially**

$$I_{\text{scatter}}(z) = I_{\text{scatter}}(0)e^{G_R I_{\text{signal}} z} \qquad (\text{for } I_{\text{scatter}} << I_{\text{signal}})$$

Props-34

Stimulated Raman Scattering (cont.)

- **See sample problem on p. 68 of text.**
- **Threshold power for "significant" Raman scattering (scattered power equals signal power)**

$$P_{\text{Raman}} \approx \frac{16 A_{\text{eff}}}{G_R L_{eff}} \qquad (G_R = 0.9x10^{-13} \text{ at } 0.694\ \mu\text{m})$$

Stimulated Brillouin Scattering

- **Similar to stimulated Raman but phonon frequency is higher**
- **Linewidth, $\Delta\nu_B$, of scattered light is narrow (~135 MHz in silica glass)**
- **Signal ("pump") is frequently wider than $\Delta\nu_B$ so we need correction factor of $\Delta\nu_B / \Delta\nu_{pump}$ to gain coefficient**

$$G_B = G_{B0}\left(\frac{\Delta\nu_B}{\Delta\nu_{\text{pump}}}\right) = \left(\frac{2\pi n^7 p_{12}^2}{c\lambda^2 \rho V_s \Delta\lambda_B}\right)\left(\frac{\Delta\nu_B}{\Delta\nu_{\text{pump}}}\right)$$

- **G_{B0} is ~$1/\lambda^2$ and is 4.5×10^{-9} cm/W at 1 μm**
- **Power threshold**

$$P_{\text{Brillouin}} \approx \frac{21 A_{\text{eff}}}{G_B L_{eff}}$$

Props-36

Self-Phase Modulation (SPM)

- **Single channel phase effect**
- **Power in signal can change *n* in material ($\Delta n = n_2 P/A_{eff}$)**
- **Pulse train passing point in fiber is time-varying power, *P(t)***
- ***P*ower variations in time cause *n* to change which causes instantaneous frequency to change (*frequency chirp)***

$$n = n_0 + \underbrace{n_2 P / A_{eff}}_{\text{index change}} \quad \text{and} \quad \phi = \omega_0 t - \frac{\omega_0 n z}{c}$$

$$\omega \equiv \frac{d\phi}{dt} = \omega_0 - \underbrace{\frac{\omega_0 n_2 z}{c A_{eff}} \frac{dP}{dt}}_{\text{Frequency "chirp"}}$$

- **Resultant frequency chirp broadens signal spectrum and increases dispersion effects**
- **Thereby decreases (bit-rate)-distance product**

Cross-Phase Modulation (XPM)

- **Multichannel effect (several wavelengths present in fiber, each carrying different data)**
- **Power fluctuations in *other* channels cause index of refraction to change, causing signal frequency to chirp**
- **Chirp broadens spectrum of signal light, causing more dispersion, and decreasing (bit-rate)-distance product**

Props-38

Four-Wave Mixing

- Also called *four-photon mixing*
- **Multichannel effect**
- **Channels "mix" or "beat" due to nonlinearity and produce inter-modulation (IM) frequencies**

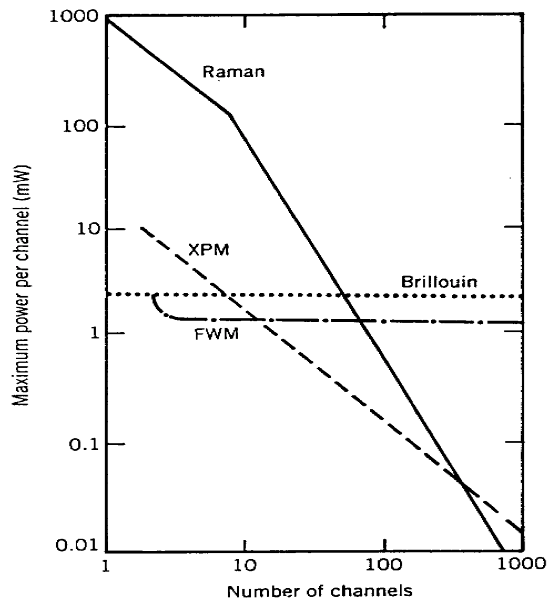
$$I = k\left|\sum_i \left(E_1 + E_2 + \ldots + E_i\right)\right|^2$$

- **If *N* signals present, *$N^2(N-1)/2$* IM frequencies result**
  - **e.g., 3 frequencies $\Rightarrow$ 9 IM frequencies**
- **If frequencies evenly spaced, some IM frequencies fall on top of some signal frequencies and cause interference**
- **Aggravated by operating near zero dispersion wavelength**
- **Solution**
  - **Reduce power**
  - **Avoid zero-dispersion wavelength region**
  - **Space channels unequally**

Props-39

Summary of Nonlinear Effects

- **Single channel: Brillouin limit (several mW)**
- **Multichannel signals (see figure)**
  - **Up to 11 channels: 4-wave mixing (<2 mW/channel)**
  - **11 to several 100 channels: cross-phase modulation limit (1 mW down to ~70 μW/channel)**
  - **>several 100 channels: Raman scattering limit (10s μW/channel)**



From A.R. Chraplvy, *J. Lightwave Technology*, vol. 8, p. 1548, 1980.

Cables

- **Goal:**
  - **Provide strength and protection** **(while minimizing cable volume and weight)**
- **Avoid adding appreciable optical loss**
- **May have power-carrying conductors**
- **Desirable cable properties:**
  - **Minimize stress-produced optical losses**
  - **High tensile strength**
  - **Immunity to water vapor penetration**
  - **Stability of characteristics in environment**
  - **Ease of handling and installation**
    - » **Compatibility with installation equipment**
  - **Low costs**
    - » **Acquisition**
    - » **Installation**
    - » **Maintenance**

Props-41

Cable Components

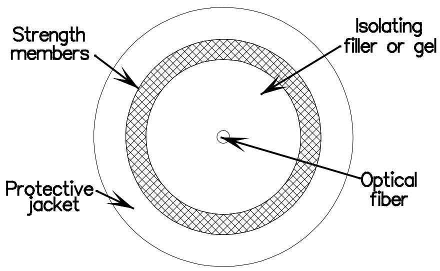
- **Optical fibers: single or multiple fibers**
- **Buffering material: soft substance around fiber**
  - **Isolate from radial compressions and localized stresses**
- **Strength members: high tensile-strength materials for longitudinal strength**
  - **High-strength, low-weight materials (e.g., Kevlar)**
- **Power conductors: copper conductors or copper-coated high-strength wires**
- **Filler yarns: take up space between strength members and provide some buffering and block water**
- **Jacket: abrasion protection; waterproofing; protection from rodents, fish, etc.; resistance to chemicals; smokeproof; nonflammable; etc.**
  - **Jacket determines installation properties**

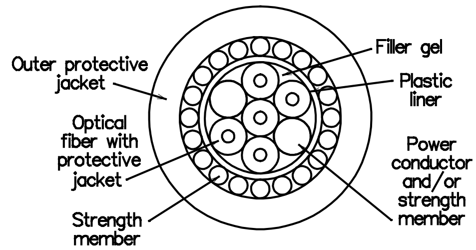
Props-42

- Buffering
  - ☞ *Loose-buffered*: fiber movable in buffer
  - ☞ *Tight-buffered*: immovable fiber
- Tensile strength of fiber cable is sum of individual strengths
  - ❖ $T = \sum EiA_i$;
  - ☞ *T* is tensile load, *S* is maximum allowed strain or elongation (e.g., 1%), E_i is Young's modulus of i-th component, and A_i is cross-section area of i-th component
- Potential problems:
  - ☞ Elongation of cable
    - ✳ Typical fiber: ~1%
    - ✳ Typical stress member: ~20% before breaking
    - ✳ Solution: wind fiber in helix inside cable

Cables (cont.)

- Wide range of installation environments
  - Ducts
  - Aerial stringing from posts
  - Trenches
  - Underwater installation
  - Laying cable on ground
- Representative duct cable (left)
- Representative aerial cable (right)

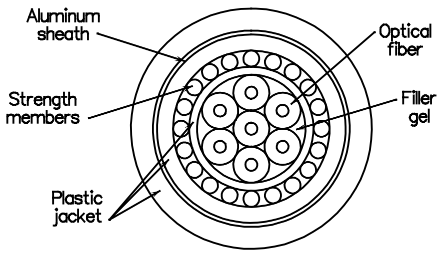


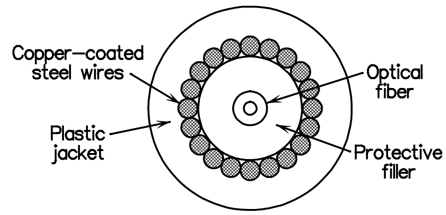


Props-43

Cables (cont.)

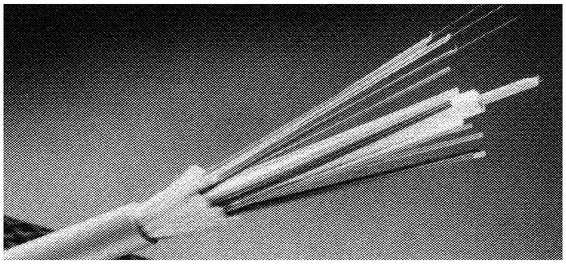
- Representative cable for burial in trenches (left)
  - More outer protective layers
- Representative cable for short-distance, undersea transmission (right)
  - Copper-clad steel wires for power and cable-strength
  - Electric power in cable can provoke defensive behavior from sharks and other fish in certain areas; cable may need extra protective layers





Props-44

Example of Fiber Cable



Fiber Properties Review

- Optical attenuation
  - Power loss in fiber (dB/km)
    - » Causes
      - Absorption and scattering in glass
      - Glass impurities, fiber imperfections, bends
    - » Minimum loss at 1550 nm

- Fiber dispersion
  - Pulse spreading limits maximum data rate
  - Causes
    - » Fiber modes
    - » *n* is function of wavelength
    - » Waveguide effects
  - Zero dispersion in SM near 1300 nm (and 1550 nm)

- Nonlinear effects
  - Accumulate over long distances
  - Limit maximum power that can be put into fiber